Lecture 9 – Friday March 29, 2013

Intelligent Control Systems

These slides are based on materials from the following books:

- Saeed Benjamin. *Introduction to Robotics: Analysis, Control, Applications*. 2nd Edition, Wiley, 2010.
- Kevin M. Passino, “Intelligent Control: An Overview of Techniques”, Chapter in: T. Samad, Ed. *Perspectives in Control: New Concepts and Applications*. IEEE Press, NJ, 2001.
- Michael Negnevistky . *Artificial Intelligence: A Guide to Intelligent Systems*. ISBN:9788131720493 Pearson.

Objectives

When you have finished this lecture you should be able to:

- Understand basic concepts of intelligent control systems.
- Understand basic concepts of fuzzy logic as intelligent control technique.

Outline

- Intelligent Control
- Fuzzy Control
- Fuzzification
- Fuzzy Sets
- Fuzzy Inference Rule Base
- Defuzzification
- Summary
- Resources

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Intelligent Control

- Artificial Intelligence (AI):

AI is the science and engineering of making intelligent machines/agents.

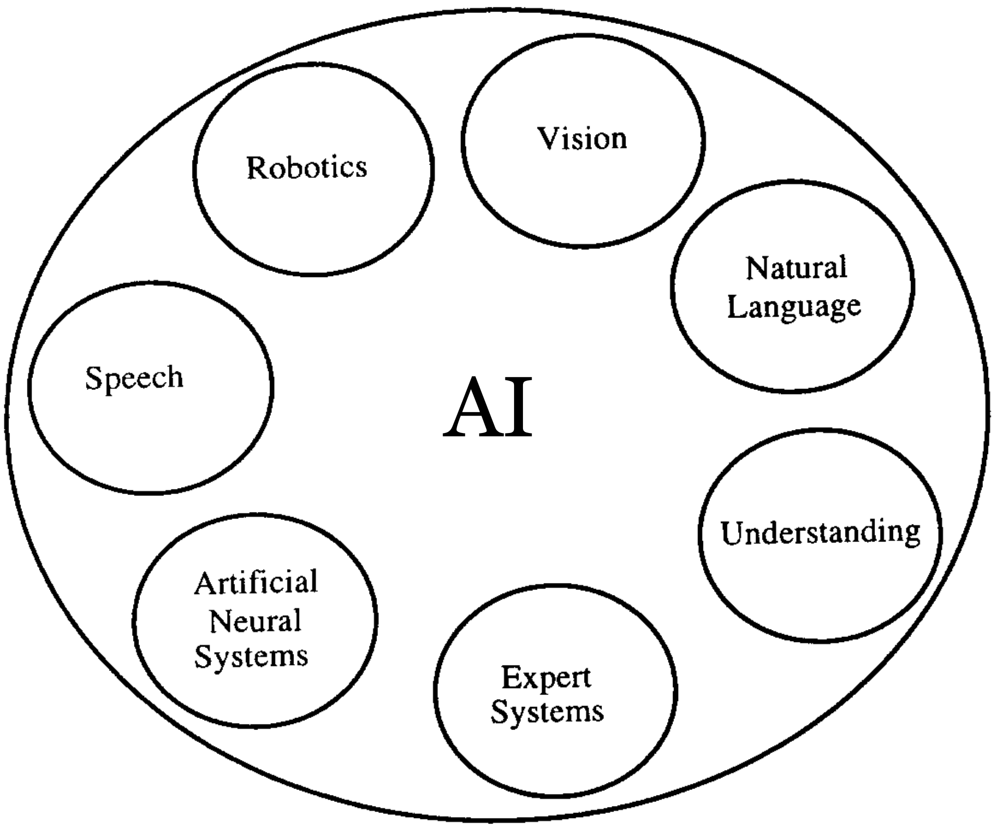
◇ Problem Solving and decision making

◇ Reasoning

◇ Learning

◇ Natural language understanding

◇ Pattern recognition



Intelligent Control

- Computational Intelligence (CI) vs. Artificial Intelligence (AI):

CI is defined as a part of computer science devoted to solution of **non-algoritmizable problems**.

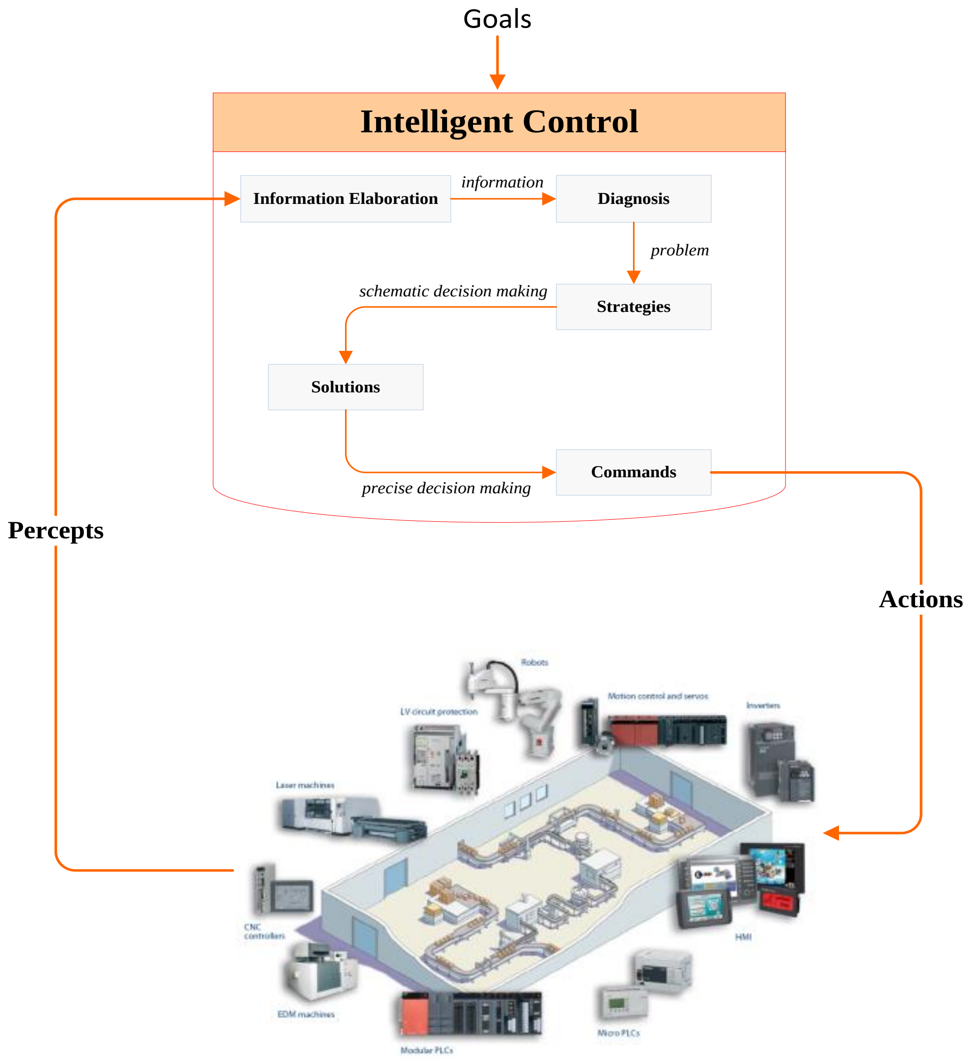
In this view **AI is a part of CI** focused on problems related to **higher cognitive functions**, while the rest of the CI community works on problems related to perception and control, or lower cognitive functions.

CI primarily includes **nature-inspired techniques** such as artificial neural networks, fuzzy logic, and evolutionary computation and swarm intelligence.

Intelligent Control

Intelligent control achieves automation via the emulation of **biological intelligence.**

It either seeks to replace a human who performs a control task (e.g., a chemical process operator) or it borrows ideas from how biological systems solve problems and applies them to the solution of control problems (e.g., the use of neural networks for control).



Intelligent Control

Data Imperfection

Uncertainty

- “I think there are two work pieces (WPs) in front of me”.
- The number is exact but we are not sure.
- The associated confidence or belief degree<1.

Imprecision

- “There are at least two WPs in front of me”.
- The number of WPs could be two or more.

Vagueness

- “The WP is wide.”
- The assigned attribute “wide” is not well-defined as it can be interpreted subjectively, i.e., have different meaning from one observer to the other.

Ambiguity

- WP width is between 2 and 5.

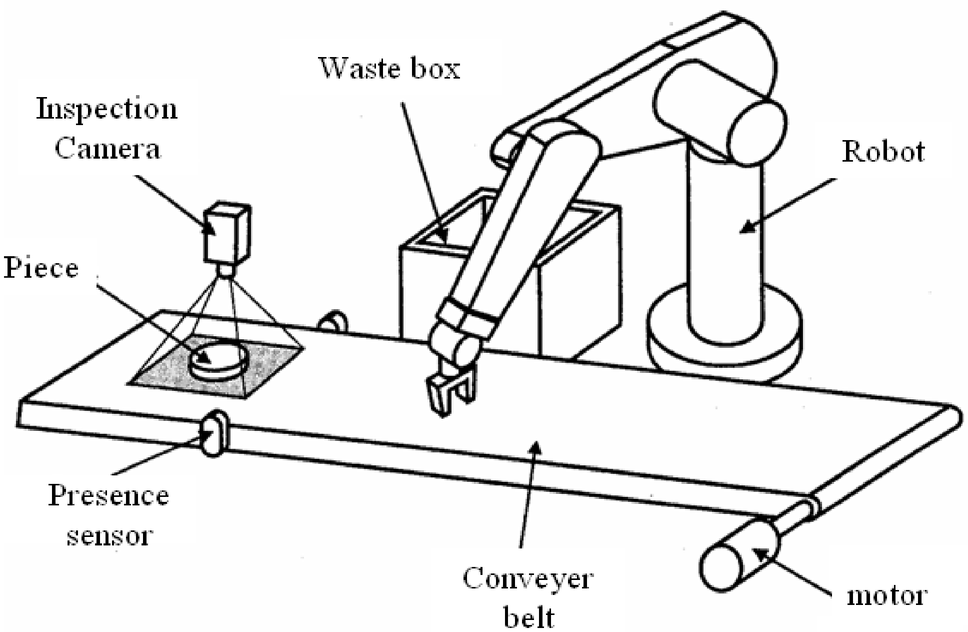
Incompleteness

- “It is not possible to pick the WP”
- Some information missing.

Source: Bahador Khaleghi, Alaa Khamis, Fakhreddine Karray, “Multisensor Data Fusion: a Review of the State-of-the-Art”, Information Fusion, Elsevier, 2010 .

Intelligent Control

- ***Example:*** A robot is picking defected work pieces and places them in a waste box
- The robot is estimating the **state of a work piece** (defected or non-defected) using its camera.
- Assume the robot's sensors are noisy.
- If **mistaking** a non-defected work piece for a defected one incurs costs (e.g., the **robot places non-defected work pieces in the waste box**).



Intelligent Control

- Intelligent Control Techniques:
  - ◇ Fuzzy Control
  - ◇ Neural Networks
  - ◇ Neuro-fuzzy control
  - ◇ Expert Systems
  - ◇ Genetic Algorithms
  - ◇ Bayesian techniques
  - ◇ Intelligent agents (Belief-Desire-Intention BDI model)
  - ◇ …

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Fuzzy Control

"*People do not require precise, numerical information input, and yet they are capable of highly adaptive control.*"

Professor Lotfi Zadeh, UC Berkeley, 1965

"The Egyptian summer is very hot and pretty dry in most of the country, and very humid in the Delta and along the Mediterranean Coast. In recent years the humidity has spread more to Cairo in August! Winter is mild with some rain, but usually it is bright, sunny days with a bit cold nights.."

As you can see, a number of "descriptors" are used in this statement to describe certain conditions that are not very clear.

Fuzzy Control

For example, when we state that the day was supposed to be very hot, what do you think it was supposed to be? 35^{o}C? Or maybe 45^{o}C?

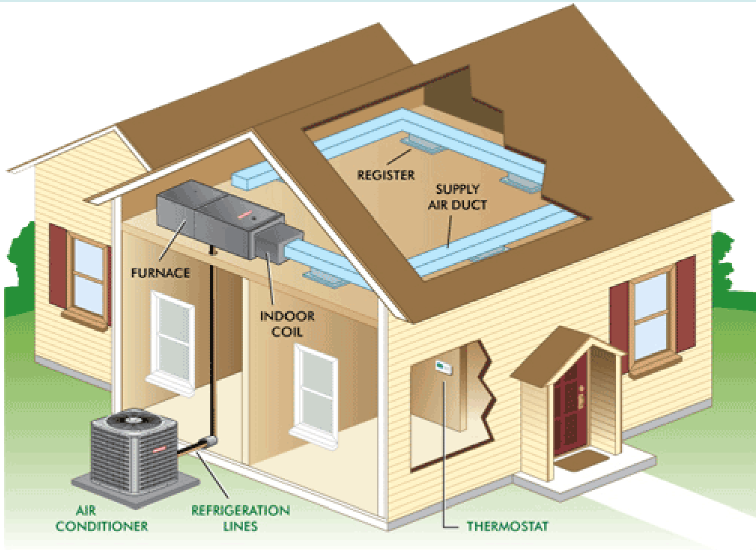
If you live in Alexandria, even 30^{o}C may be too hot.

If you live in Aswan, 30^{o}C is not too hot.

Then, as you can see, this description of the temperature is, in fact, fuzzy.

Fuzzy Control

Consider a temperature control thermostat. Suppose we want to control the temperature at 23^{o}C such that if the temperature is higher, the air conditioning turns on; if it is cooler, it turns off.



Air Conditioning (A/C)

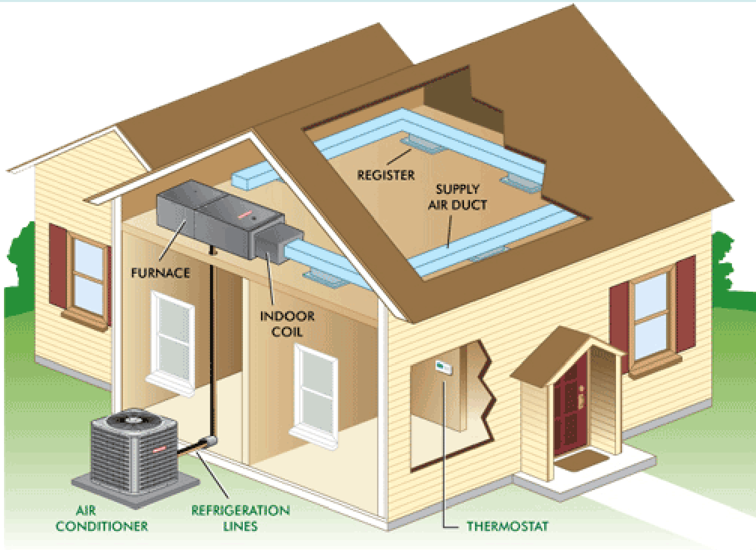
To do this, we want to set the thermostat control to 23^{o}C.

IF TEMPERATURE $\geq 23^{O}$ TURN ON A/C

This means that as soon as the temperature is 23 or more, the air conditioning will turn on. However, as you notice, the system will not turn on even if temperature is 22.9.

Fuzzy Control

One way to improve the flexibility of this control statement is to add another statement to it that would turn on the air conditioning at slightly lower temperature but at a slightly lower power setting (assuming it is possible to change the power setting of the air conditioning system), resulting in the following:



Air Conditioning (A/C)

IF TEMPERATURE $\geq 23^{O}$ TURN ON A/C 90% FULL_POWER

IF TEMPERATURE $\geq 26^{O}$ TURN ON A/C FULL_POWER

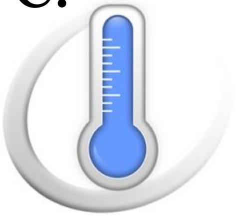
Fuzzy Control

- Control Statements

IF TEMPERATURE $\geq 23^{O}$ TURN ON A/C 90% FULL_POWER

IF TEMPERATURE $\geq 26^{O}$ TURN ON A/C FULL_POWER

- A major problem with this type of control statements is that if we intend to have control over a very large range of values, hundreds of this type of statements will be necessary to cover small variations to desired values.
- Imagine that we want to have control over every 0.1^{o}C variation in temperature in a chemical process, which may vary 10^{o}C.
- There would be about 200 control statements!



Fuzzy Control

- Crisp Values versus Fuzzy Values:

IF	TEMPERATURE	≥	23^{O}	TURN	ON A/C

Crisp value

IF	TEMPERATURE	≥	HOT	TURN	ON A/C

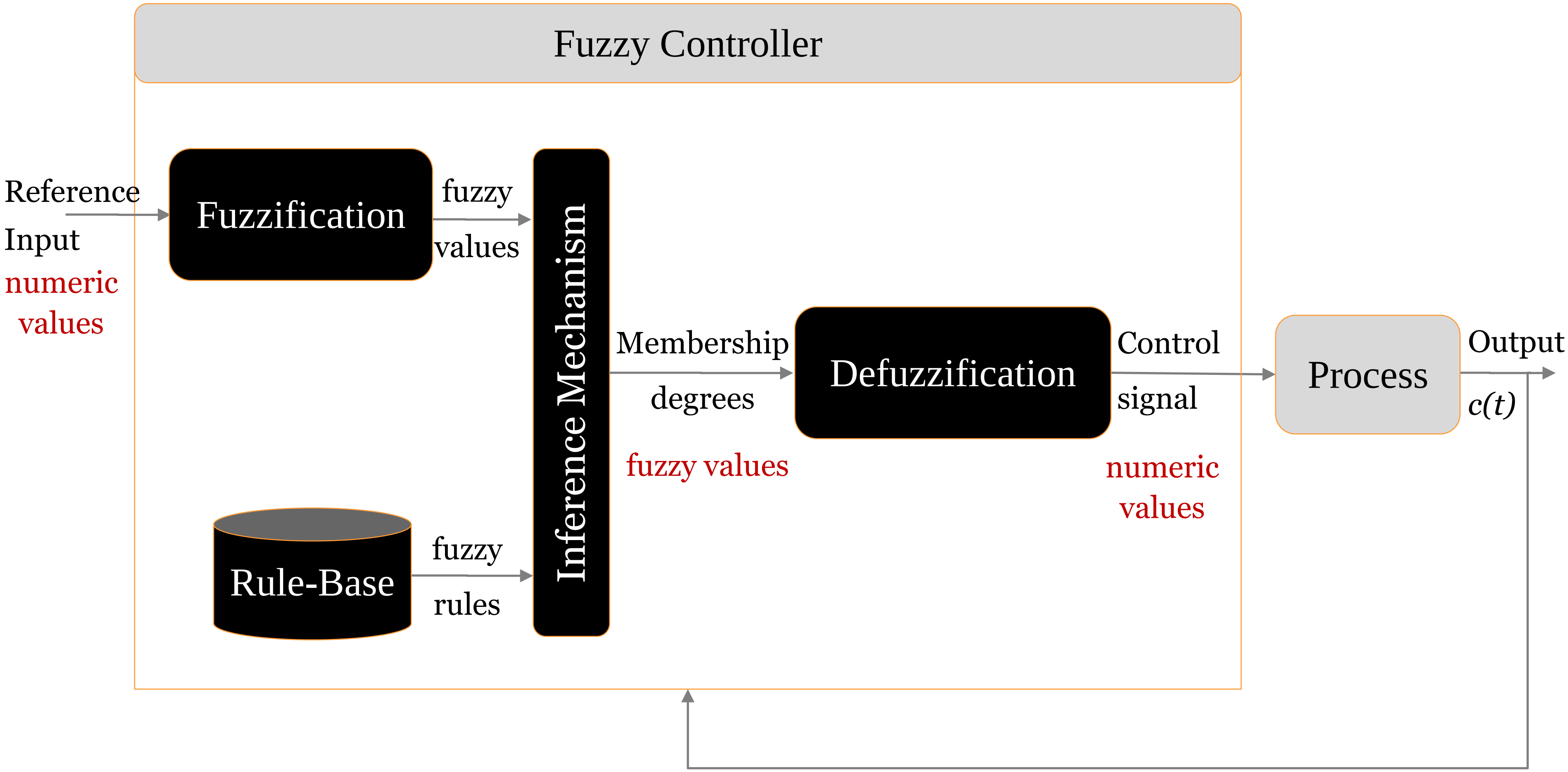
Fuzzy value

◇ A crisp value is a clearly defined value with one interpretation. A crisp value of 23^{O}C means the same in any system, and it is a clearly defined and measurable value. It is also called a singleton.

◇ In contrast, a fuzzy value is unclear and may be interpreted differently depending on the circumstances.

Fuzzy Control

Fuzzy control is a methodology to represent and implement a (smart) human's knowledge about how to control a system.



Outline

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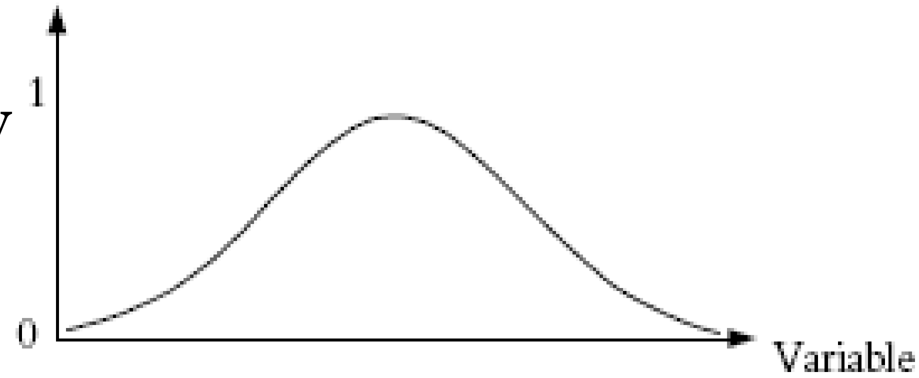
Fuzzification

- Fuzzification is the process of converting input and output values into their membership functions.
- The result of fuzzification is a set of graphs or equations that describe the degree of membership of different values in different fuzzy variables.
- Common Membership Functions:
  - ◇ Gaussian membership function: this is a natural way to represent a distribution.

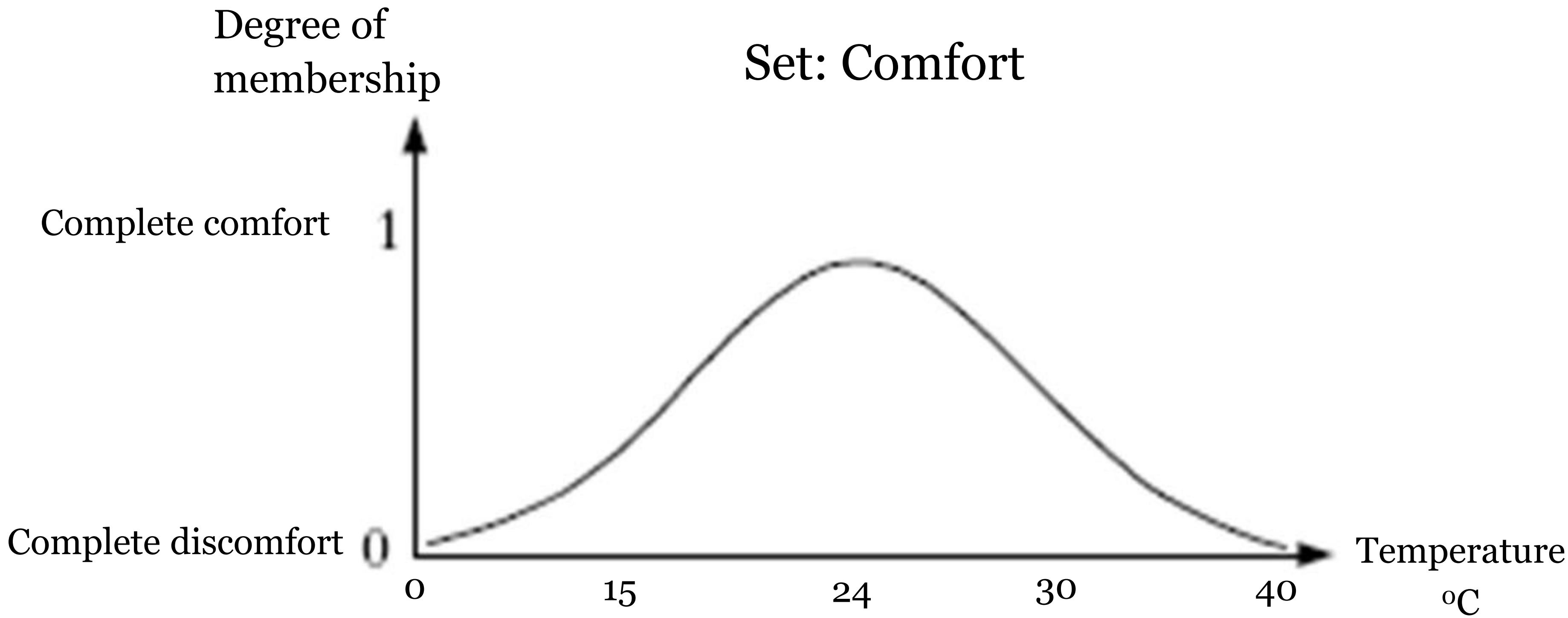


Gaussian representation used to be modified into simpler forms for easier application.

Fuzzification

- Common Membership Functions (cont'd):
  - Common Membership Functions:

Variable: Comfortable temperature for human activity

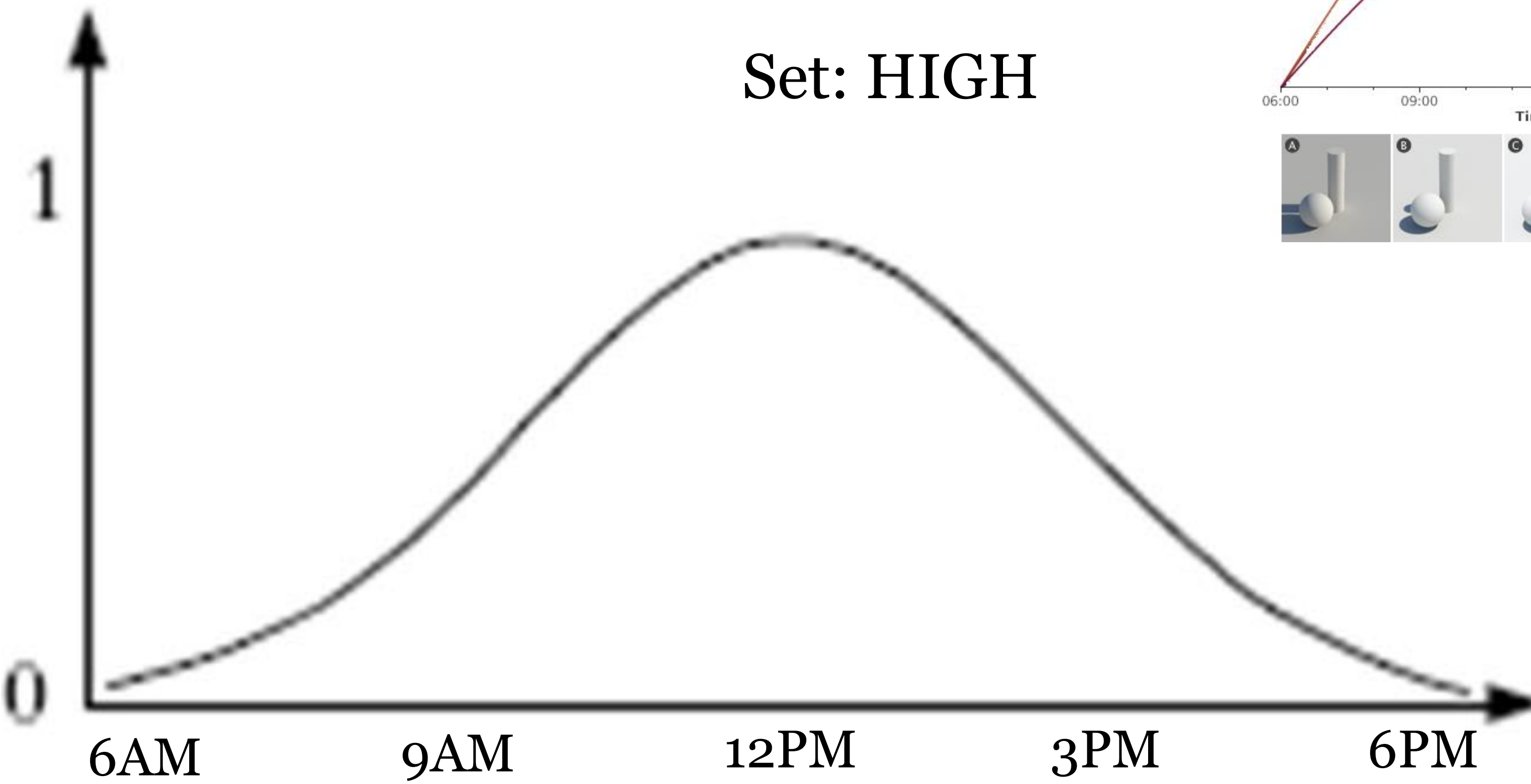


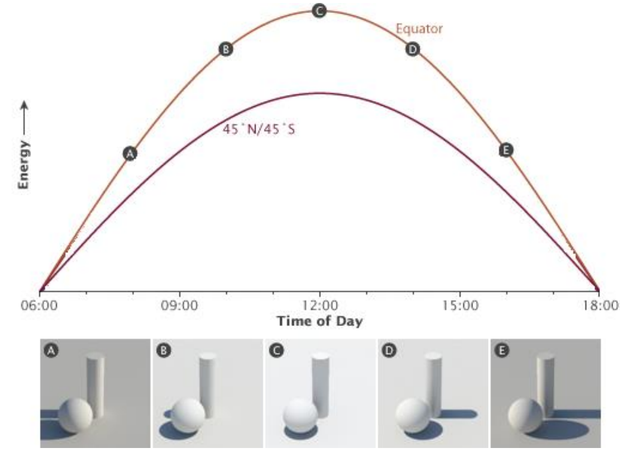
Fuzzification

- Common Membership Functions (cont’d):
  - Common Membership Functions:

Variable: Solar energy

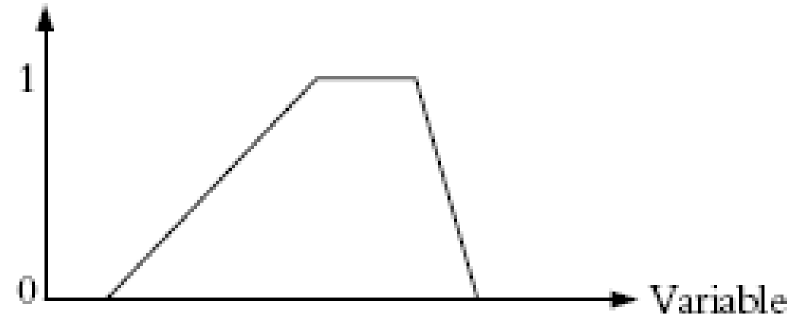
Set: HIGH





Fuzzification

- Common Membership Functions (cont'd):
  - ◇ Trapezoidal membership function: used to represent a Gaussian function in a simpler way.

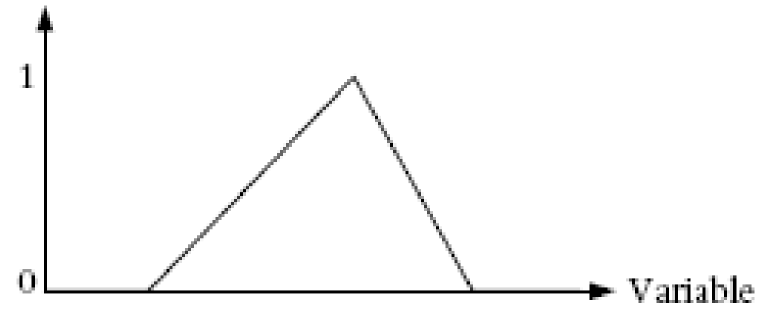


Here, the membership function is represented by three simple lines, requiring only four points.

Each section is a straight line between successive points, and therefore, the degree of membership for each value of the variable can easily be calculated from the line equations.

Fuzzification

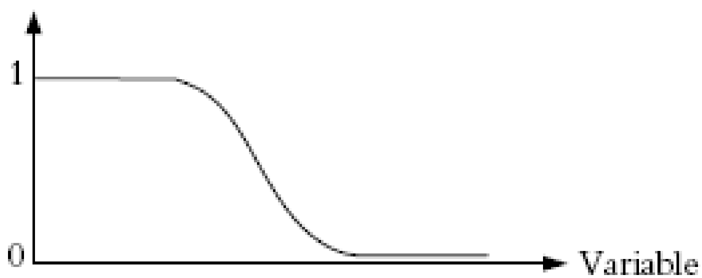
- Common Membership Functions (cont'd):
  - ◇ Triangular membership function: This is also a very common membership function that simplifies a Gaussian function, requiring only three points.



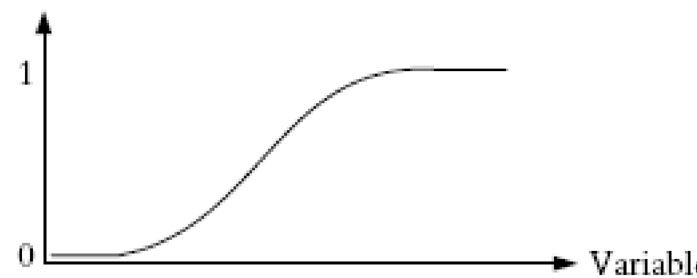
As shown in the figure, each section is a straight line between successive points. Degrees of membership for each value of the variable are simply calculated from the line equations.

Fuzzification

- Common Membership Functions (cont'd):
  - ◇ Z-shaped and S-shaped membership functions: These second-order functions may be used to represent the upper and lower limits of a variable, where the degrees of membership may remain the same (0 or 1) for a range of values. A trapezoidal membership function with a vertical left or right side may be used as a simple model for S- and Z-shaped functions.



Decreasing (Z curve) sigmoidal membership functions

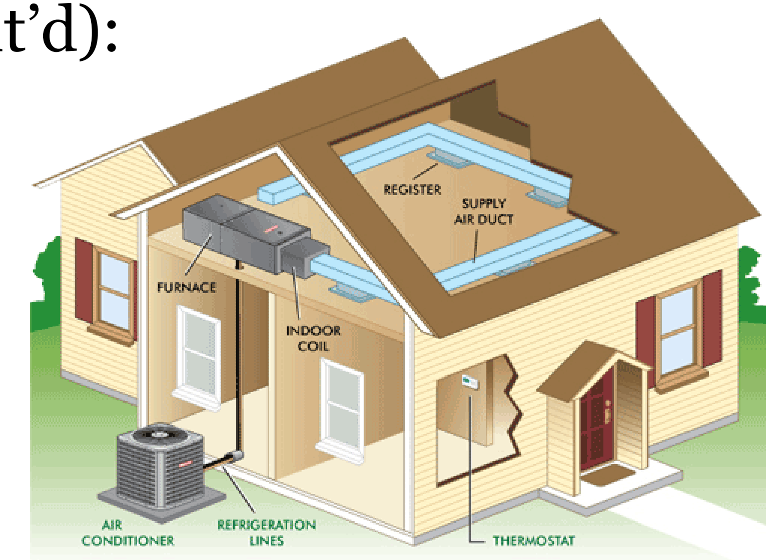


Increasing (S curve) sigmoidal membership functions

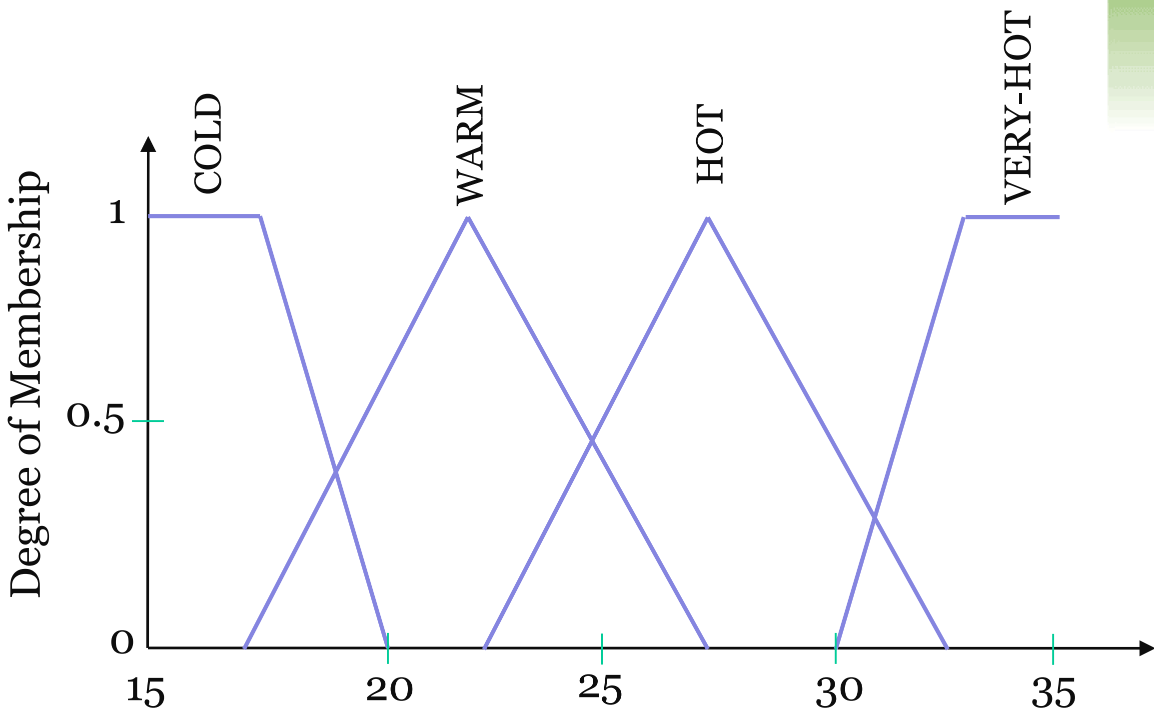
Fuzzification

- Common Membership Functions (cont'd):

  Example: To define the temperature variable in fuzzy form, we divide the desired range into a number of sets.

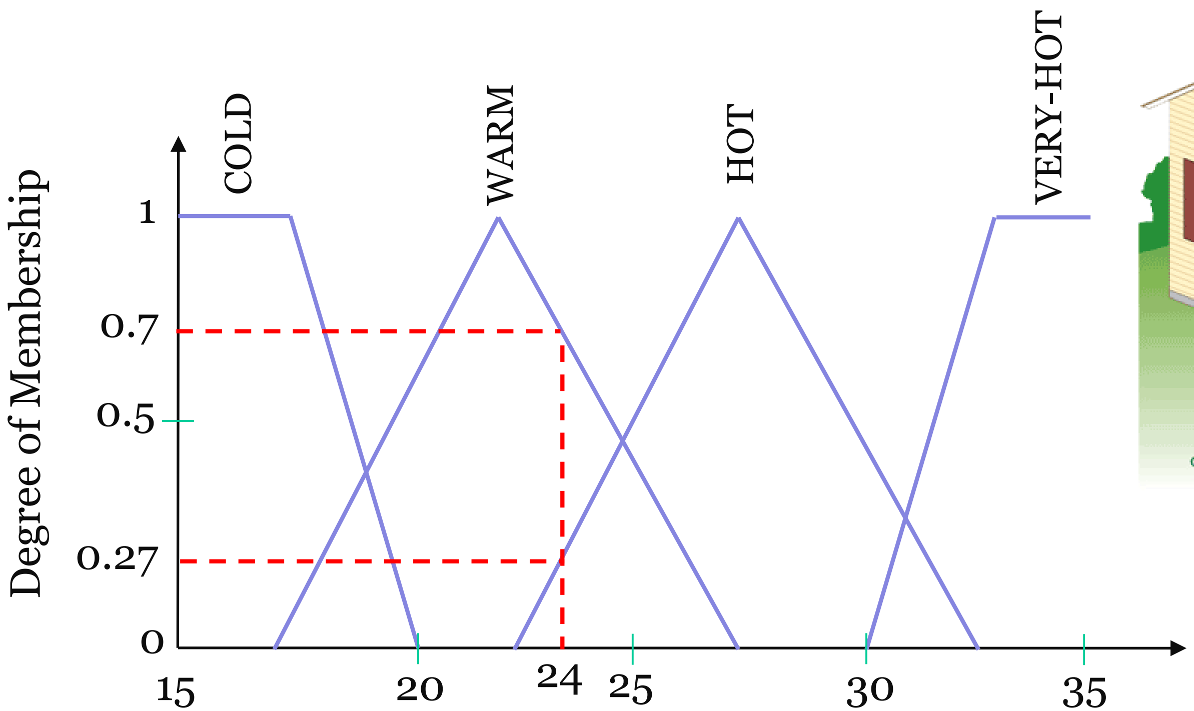


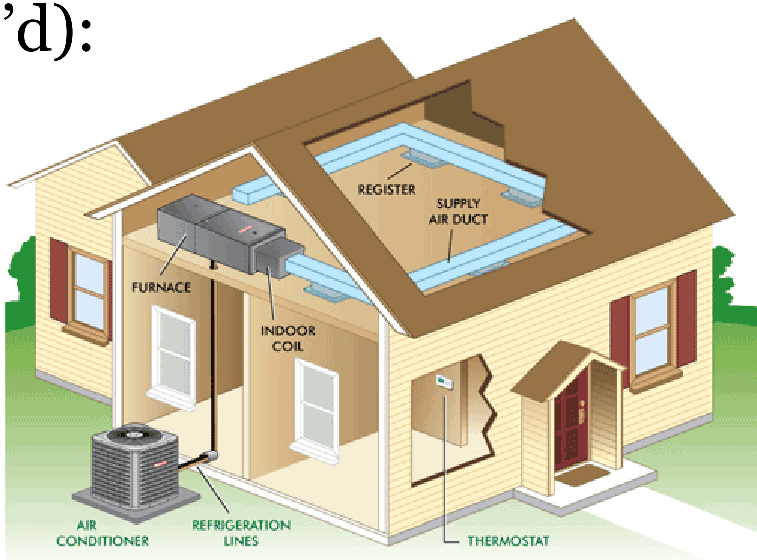
Air Conditioning (A/C)



Fuzzification

- Common Membership Functions (cont'd):





Air Conditioning (A/C)

VERY-HOT: @30,0, @32,1, @35,1
HOT: @22,0, @27,1, @32,0

Temperature=24 has 70% degree of membership in WARM set and 27% in HOT set.

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Fuzzy Sets

To be able to use a fuzzy description in a control setting, we define a fuzzy set whose members describe the fuzzy variable at different degrees of membership or truth.

- Crisp Rule: IF RULE THEN CONSEQUENCE

  If RULE is 100% true, CONSEQUENCE will be executed.

  Example: consider a washing machine and the following crisp statement:

  IF WATER_SAMPLE=CLEAN_WATER THEN WASH_TIME=0

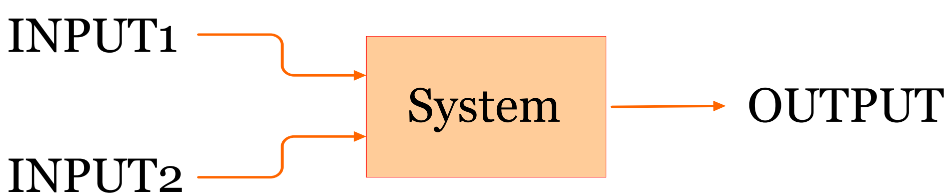
  Water must be 100% clean to stop the washing machine. CLEAN_WATER, a purely clean water sample will have a degree of membership of 100% (or 1) in the fuzzy set.

Washing Machine

Fuzzy Sets

- Fuzzy Rule:

  Assuming that two input variables called INPUT1 and INPUT2 are used in a system to control an output variable called OUTPUT, we may write a general set of rules as:



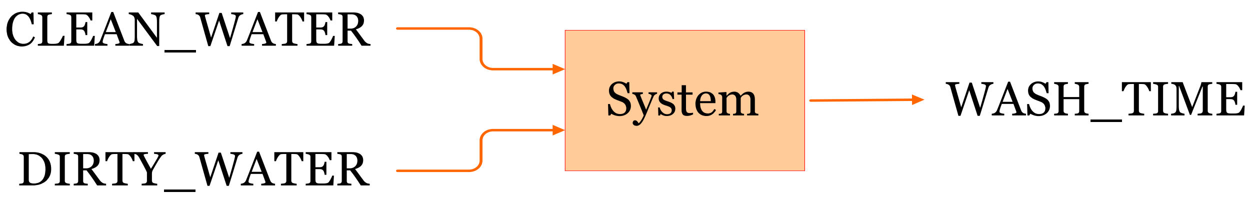
IF INPUT1 = degree-of -membership in INPUT1-SET AND

INPUT2 = degree-of -membership in INPUT2-SET THEN

OUTPUT = degree-of-membership in OUTPUT-SET

Fuzzy Sets

- Fuzzy Rule:



Washing Machine

IF CLEAN_WATER = 90% AND DIRTY_WATER = 15% THEN

WASH_TIME = 10% OF CYCLE_TIME

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Fuzzy Inference Rule Base

Fuzzy Inference Rule Base is the controller part of the system and is based on truth table logic. The rule base is a collection of rules related to the fuzzy sets, the input variables, and the output variables and is meant to allow the system to decide what to do in each case.

IF <Condition> THEN <Consequence>

IF < Condition 1 AND(OR) Condition 2> THEN <Consequence >

IF < Condition 1 AND(OR) Condition 2> THEN <Consequence1 AND(OR) Consequence 2>

Ex.

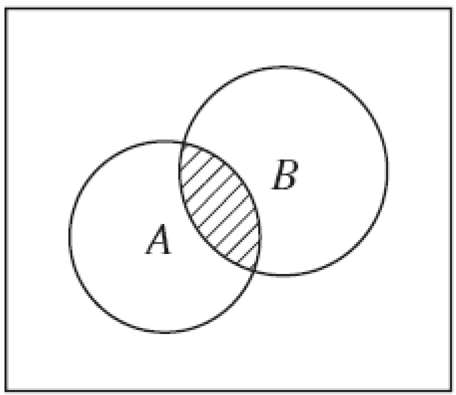
If temperature is HOT and humidity is HUMID Then power is HIGH

If temperature is LOW or humidity is HUMID Then power is LOW

Fuzzy Inference Rule Base

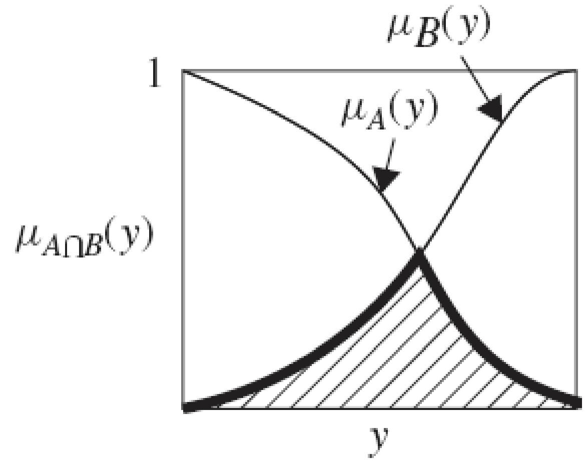
- Intersection

Crisp Set



A and B:A ∩ B

Fuzzy Set



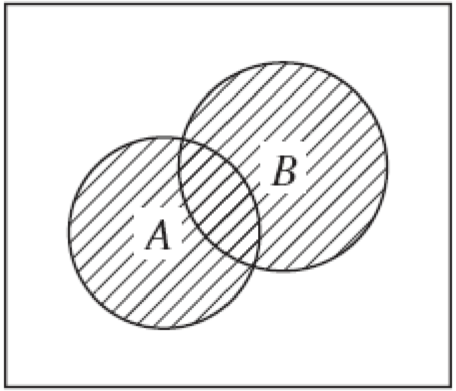
- The result of an "and" operation is the minimum of the two values.

$$u_A = 0.5, \quad u_B = 0.1 \quad \Rightarrow \quad u_A \cap u_B = \min\left[u_A, u_B\right] = 0.1$$

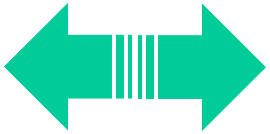
Fuzzy Inference Rule Base

- Union

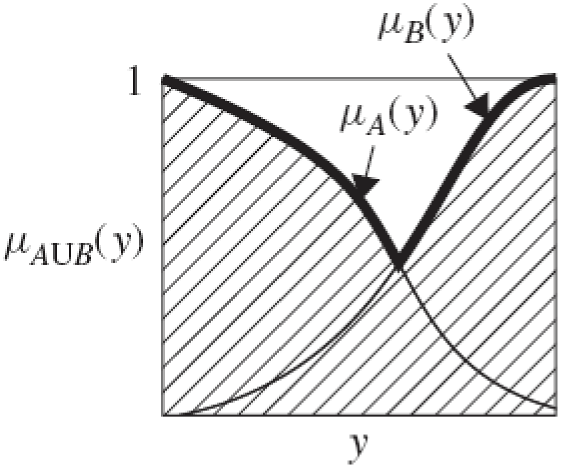
Crisp Set



A or B or both: A ∪ B



Fuzzy Set



- The result of an "or" operation is the maximum of the two values.

$$u_A = 0.5, \quad u_B = 0.1 \quad \Rightarrow \quad u_A \cup u_B = \max[u_A, u_B] = 0.5$$

Fuzzy Inference Rule Base

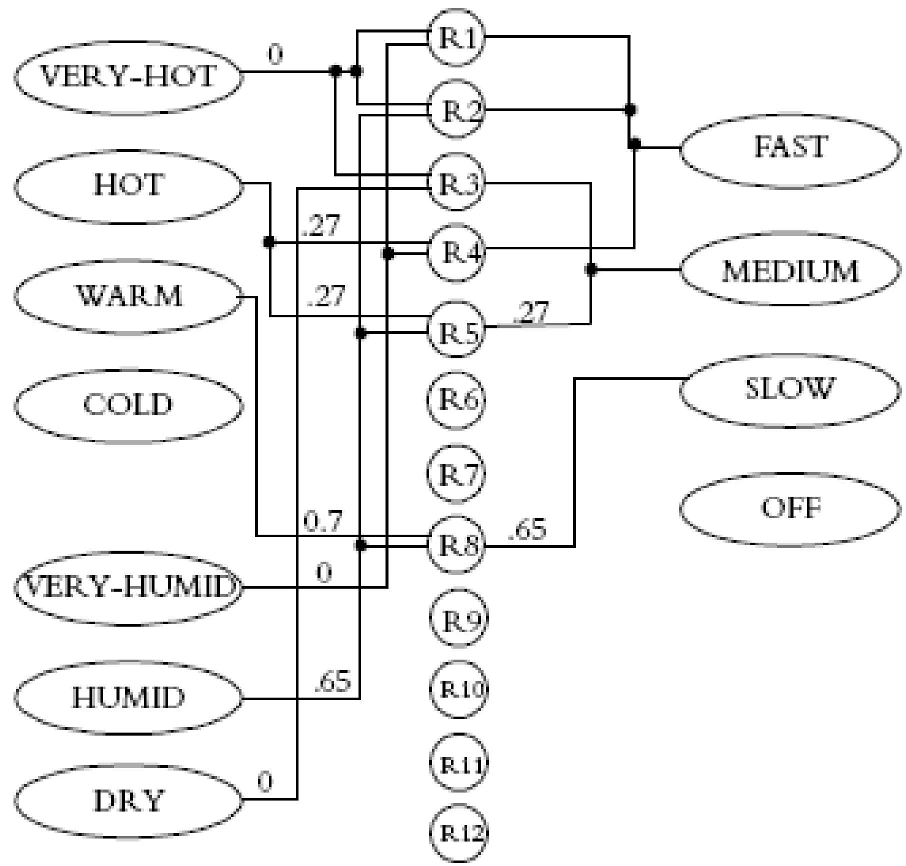
- The total number of rules in a rule base is equal to the product of the numbers of sets of each input variable.

- *Example:* if there are three input variables, with m, n, and p fuzzy sets, the total number of rules:

$$\text{Temperature set}: m = 4$$

$$\text{Humidity set}: n = 3$$

$$R = m \times n = 4 \times 3 = 12$$



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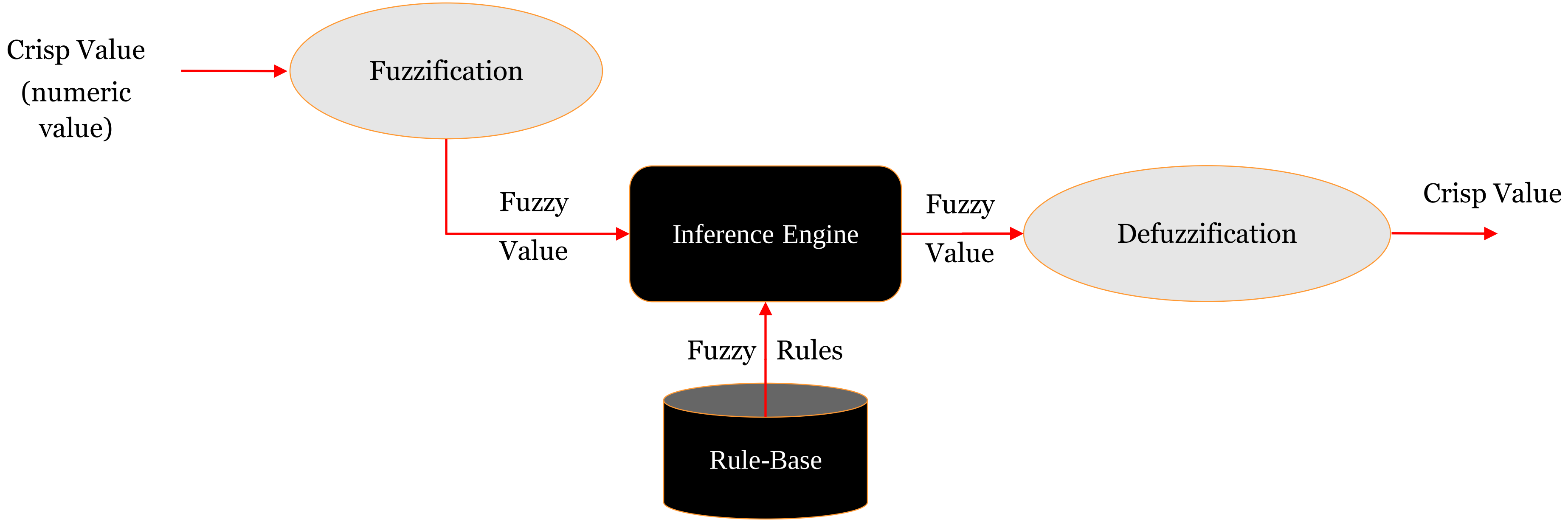
Defuzzification

- Defuzzification is the conversion of a fuzzy output value to an equivalent crisp value for actual use.
- As the fuzzy rules are evaluated and corresponding values are calculated, the result will be a number related to the corresponding membership values for different output fuzzy sets.



Defuzzification

- *Example:*

  Suppose that the output power setting for an air conditioning system is fuzzified into OFF, LOW, MEDIUM, and HIGH.

  The result of rule base evaluation may be, say, a 25% membership in LOW and a 75% membership in MEDIUM.

  Defuzzification is the process of converting these values into a single number that can be sent to the air conditioning controller.

Defuzzification

Defuzzificaion Methods

Center of Gravity method

Mamdani's Inference Method

Defuzzification

- Center of Gravity Method:
  1. Multiply the membership degrees for each output variable by the singleton value of the output set.
  2. Add all of the above together and divide by the summation of output membership degrees.

Defuzzification

- Center of Gravity Method:

  Example: suppose the values obtained for the output of the air conditioning system membership sets are:

  0.4 for LOW and

  0.6 for Medium,

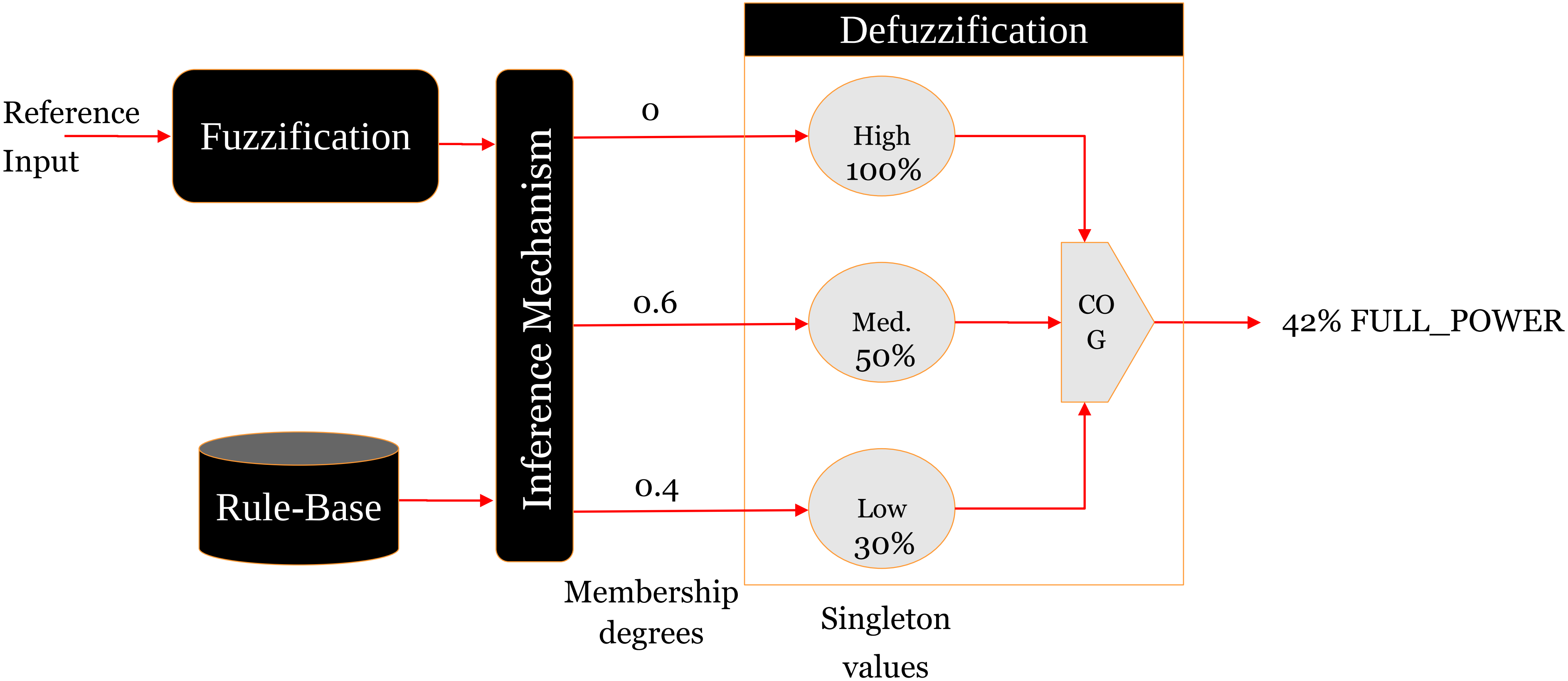
  and further suppose that the singleton value:

  for LOW is 30% and

  for MEDIUM is 50% of full power.

Defuzzification

- Center of Gravity Method:



The output value for the air conditioning would then be:

$$Output = \frac{0.4 \times 30\% + 0.6 \times 50\%}{0.4 + 0.6} = 42\%$$

Defuzzification

- Mamdani's Inference Method:
  1. Fuzzification of the input variables,
  2. Rule evaluation;
  3. Aggregation of the rule outputs, and finally
  4. Defuzzification

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Defuzzification

- Mamdani's Inference Method:

Example: Let's examine a simple two-input one-output problem that includes three rules:

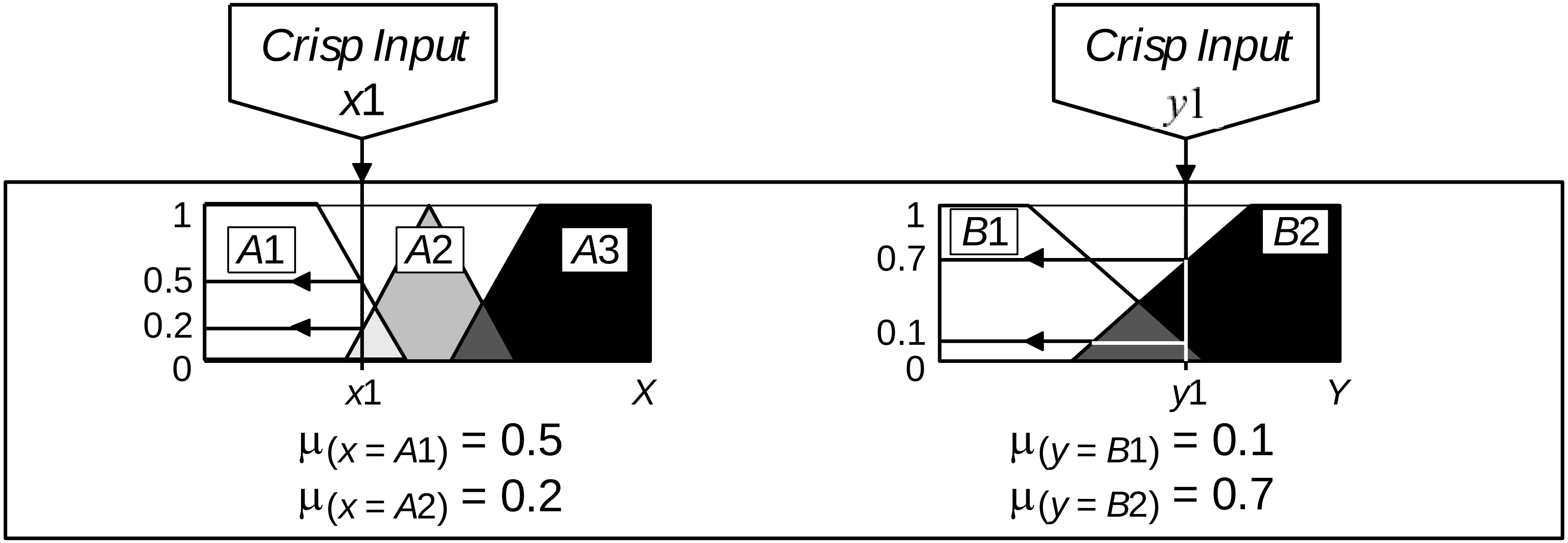
RULE:1 IF *x* is A3 OR *y* is B1 THEN *z* is C1	RULE:1 IF *temperature* is high OR *humidity is dry* THEN *turn A/C high*
RULE:2 IF *x* is A2 AND *y* is B2 THEN *z* is C2	RULE:1 IF *temperature* is moderate AND *humidity is high* THEN *turn A/C medium*
RULE:1 IF *x* is A1 THEN *z* is C3	RULE:1 IF *temperature* is low THEN *turn A/C low*

Defuzzification

- Mamdani's Inference Method:

Step-1: Fuzzification of the input variables

The first step is to take the crisp inputs, *x1* and *y1* (temperature and humidity), and determine the degree to which these inputs belong to each of the appropriate fuzzy sets.



Defuzzification

- Mamdani's Inference Method:

Step-2: Rule Evaluation

OR fuzzy operation:

$$\mu_A \cup \mu_B(x) = \max [\ \mu_A(x),\ \ \mu_B(x)]$$

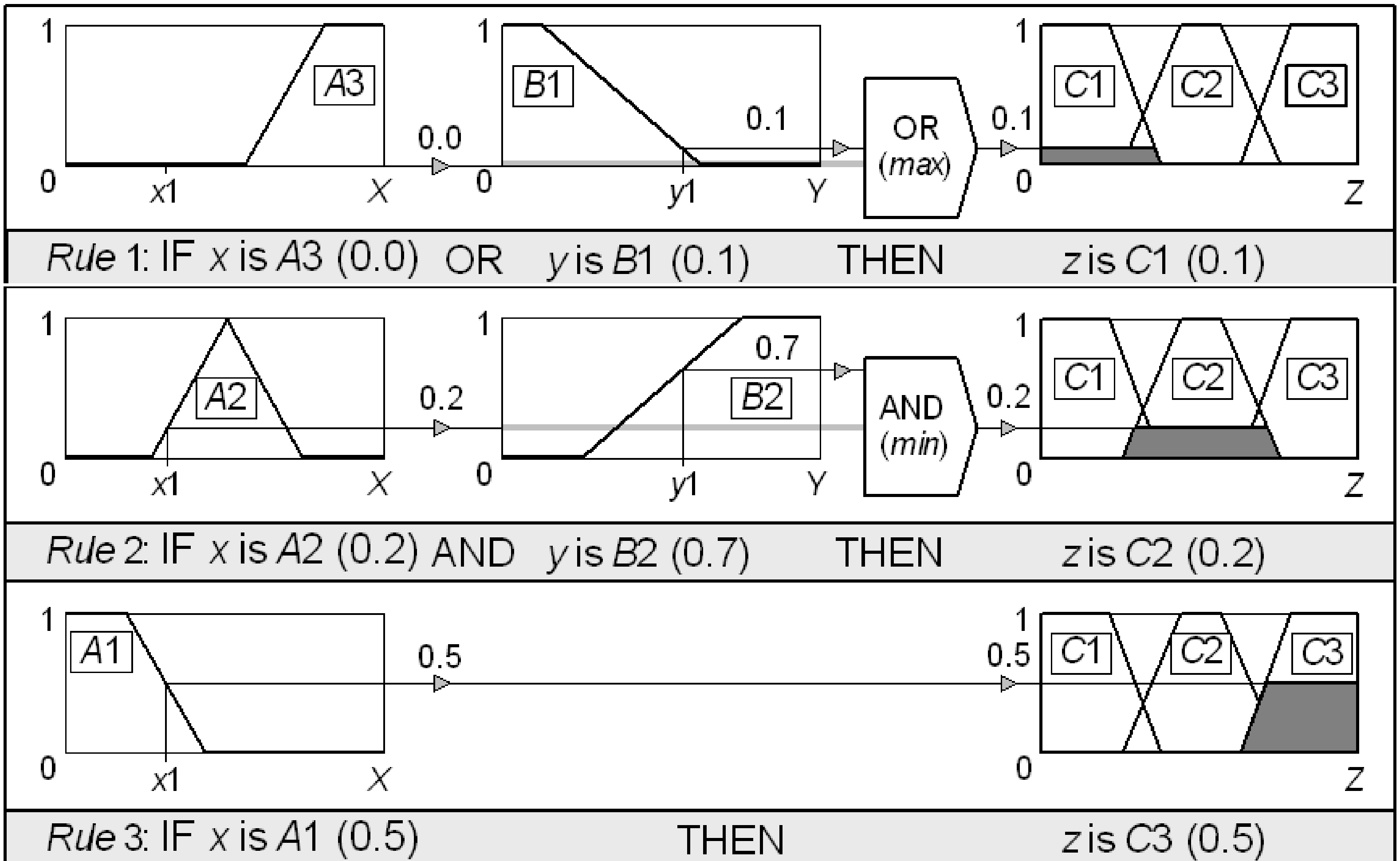
AND fuzzy operation:

$$\mu_A \cap \mu_B(x) = \min [\ \mu_A(x),\ \ \mu_B(x)]$$

Defuzzification

- Mamdani's Inference Method:

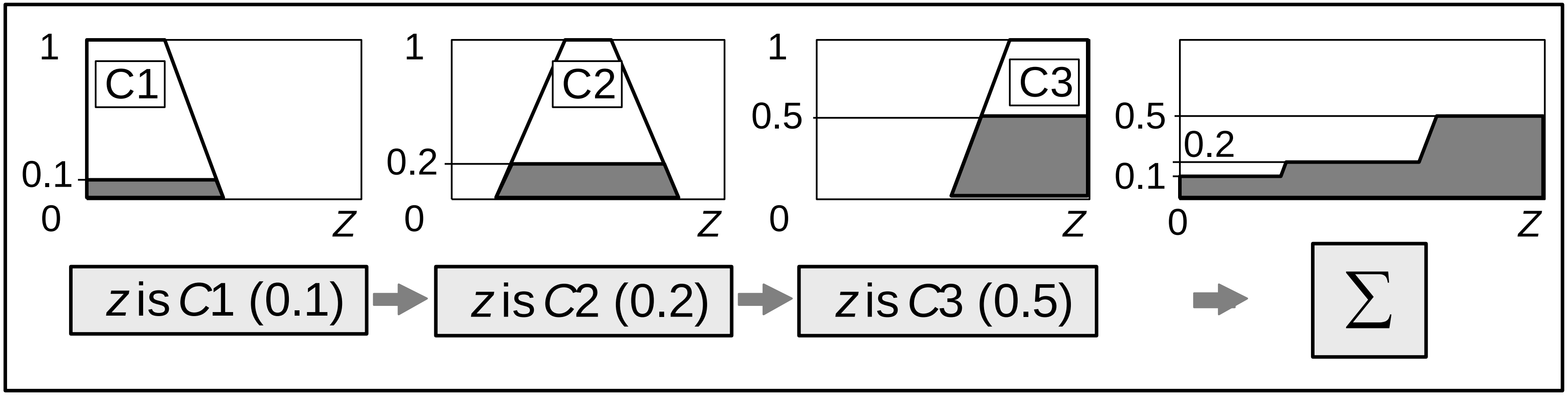
Step-2: Rule Evaluation



Defuzzification

- Mamdani's Inference Method:

  Step 3: Aggregation of the rule outputs



The remaining truncated membership functions are added with an "or" function in order to consolidate them into one area describing the output.

Defuzzification

- Mamdani's Inference Method:

  Step 4: Defuzzification

  There are several defuzzification methods, but probably the most popular one is the centroid technique. It finds the point where a vertical line would slice the aggregate set into two equal masses. Mathematically this centre of gravity (COG) can be expressed as:

$$COG = \frac{\int_a^b \mu_A(x)\, x\, dx}{\int_a^b \mu_A(x)\, dx}$$

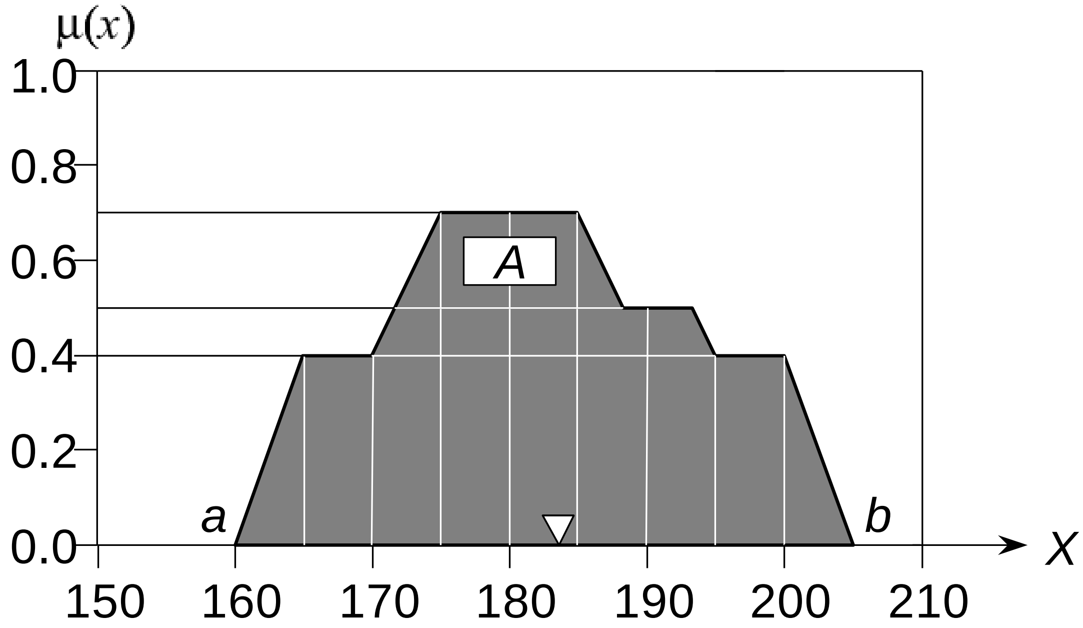
Defuzzification

- Mamdani's Inference Method:

  Step 4: Defuzzification

  ◇ Centroid defuzzification method finds a point representing the centre of gravity of the fuzzy set, A, on the interval, ab.

  ◇ A reasonable estimate can be obtained by calculating it over a sample of points.

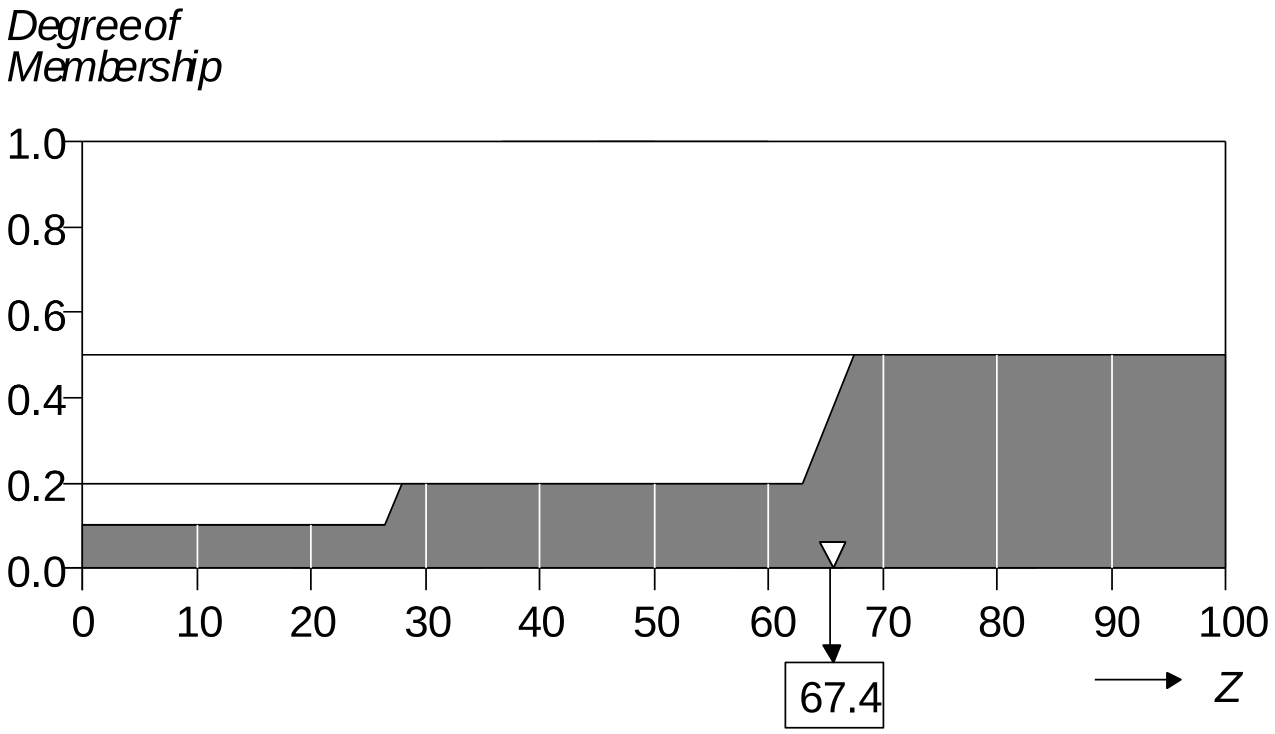


Defuzzification

- Mamdani's Inference Method:

Step 4: Defuzzification

$$COG = \frac{(0+10+20)\times 0.1+(30+40+50+60)\times 0.2+(70+80+90+100)\times 0.5}{0.1+0.1+0.1+0.2+0.2+0.2+0.2+0.5+0.5+0.5+0.5} = 67.4$$



Defuzzification

- Example:

Michael Negnevistky . *Artificial Intelligence: A Guide to Intelligent Systems*. ISBN:9788131720493 Pearson.

Available at:
http://petro.tanrei.ca/fuzzylogic/index.html

Outline

- Intelligent Control
- Fuzzy Control
- Fuzzification
- Fuzzy Sets
- Fuzzy Inference Rule Base
- Defuzzification
- Summary
- Resources

Summary

- Fuzzy logic is a very powerful way of including nonexact concepts in everyday systems, including definitions (e.g. temperature, humidity), feelings (e.g. pain, hot, cold), and adjectives (e.g. much, less). Fuzzy logic systems may be applied to countless different situations in mechatronics systems.
- In Mamdani's Inference Method, each output membership function is truncated at its corresponding membership value, which is found from the rule base. The remaining truncated membership functions are added with an "or" function in order to consolidate them into one area describing the output. The center of gravity of the consolidated area is calculated as the crisp output value.

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Resources

- Matlab Fuzzy Logic Toolbox: http://www.mathworks.com/products/fuzzy-logic/index.html;jsessionid=03ebe369ddf4a1e5a4748fa579f2 Last accessed: Nov. 8, 2012.
- NI LabVIEW PID and Fuzzy Logic Toolkit. Last accessed: Nov. 8, 2012.
- From PID to Fuzzy Control: http://www.mstarlabs.com/control/fuzzypid.html Last accessed: Nov. 8, 2012.
- Fuzzy control: http://www.atp.ruhr-uni-bochum.de/rt1/syscontrol/node131.html Last accessed: Nov. 8, 2012.
- Mamdani's Inference Method: http://www.dma.fi.upm.es/java/fuzzy/fuzzyinf/main_en.htm Last accessed: Nov. 8, 2012.